BELLCOMM, INC.
955 L'ENFANT PLAZA NORTH, S.W. WASHINGTON, D. C. 20024

B70 03041

SUBJECT: AOT Star Chart Compensation for LM Landing Attitude Deviations Case 310

DATE: March 13, 1970

FROM: K. M. Carlson

ABSTRACT

A means of compensating the LM AOT fields of view shown on star charts for LM landing attitudes other than nominal is described. Charts are developed which allow the center of the AOT detent fields of view to be located for any attitude deviations. In most cases, the orientation of the detent reticle can also be found. The field of view locator charts are designed for use with the star charts developed by T. L. Yang. A user's guide is included which provides complete instructions for use of the charts without requiring the user to go into the details of their development.

(NASA-CR-112393) AOT STAR CHART COMPENSATION FOR LM LANDING ATTITUDE DEVIATIONS (Bellcomm, Inc.) 20 p

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MEMORANDUM FOR FILE

References 1 through 3 present charts which show the stars visible in each of the Alignment Optical Telescope (AOT) detents for the lunar surface portion of the Apollo 11 through 13 missions. These star charts attempt to display the view in the AOT exactly as it would appear to the astronaut on the lunar surface.

In preparing the charts, it is assumed that the LM lands level (+x body axis along the local vertical) with the +z body axis in the direction of the nominal landing site approach azimuth. Deviations from the assumed attitude* will cause an apparent shift of the field of view as depicted on the star charts, as well as an apparent rotation of the reticle. This memorandum presents charts which enable the user to adjust the field of view as presented on the star charts to compensate for the attitude deviations. Except for the front and rear detents, these charts also show how to rotate the star chart reticle pattern in order to get the star pattern right side up as viewed in the AOT. The reticle rotation information is of secondary importance since, once the field of view is established, the reticle rotation can be easily determined by comparing the star pattern shown on the chart with what is actually observed in the AOT. Deletion of this information from the charts for the front and rear detents makes them substantially easier to use.

The attitude deviation information required to work with these charts is obtained from the DSKY display of the IMU gimbal angles, which should be read after landing while the IMU is still aligned in the landing site alignment.

The last section of this memorandum is a user's guide which provides instructions for the use of the charts without going into the details of their development.

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*Apollo 11, for example, landed with a deviation of about thirteen degrees in yaw and about four degrees in pitch.

Derivation of the AOT Detent Field of View Locator

The astronaut in the LM has two primary sources of attitude information, the flight director attitude indicator (FDAI) ball, and the DSKY display of the IMU gimbal angles. However, the FDAI ball does not provide complete roll information, while a direct numerical readout of the IMU gimbal angles is available on the DSKY. Thus, the DSKY was chosen as the source of the attitude errors. With the IMU in the landing site alignment, the gimbal angles will all be zero at the time of landing if the LM lands with the same attitude as was assumed for the star charts. Thus, the actual IMU gimbal angles at landing provide a direct measure of the attitude deviation information required. The IMU gimbal angles are "order dependent", that is, the roll deviation (middle gimbal rotation) is measured in a coordinate system which has already been yawed (outer gimbal rotation), and the pitch deviation (inner gimbal rotation) is measured in a coordinate system which has already been yawed and rolled.

As a first attempt at a solution to the problem, a chart was constructed in the following manner. First, the apparent location of the center line of a particular detent was plotted as a function of yaw deviation only. Superimposed on this, a series of plots of apparent center line deviation as a function of roll deviation was plotted for several values of yaw deviation. Lastly, for each of several values of yaw and roll deviations, plots of apparent center line deviation as a function of pitch deviation were added. The result was a very confusing array of lines, but some simplifying approximations became evident.

For the side detents (detents 1, 3, 4, and 6) it was noticed that the centerline traces for pitch deviations form a family of curves lying parallel to one another. This was true for all pitch traces, regardless of the combinations of yaw and roll deviations, though the point for zero pitch is different in each case. Taking advantage of this, the charts in Figures 1 through 4 were prepared, one for each of the side detents. The red lines are plots of the centerline motion as a function of yaw deviation for zero pitch deviation and a constant roll deviation. These plots are provided for roll deviations from -20 degrees to +20 degrees in increments of 5 degrees. The green lines are plots of the centerline motion as a function of roll deviation for zero pitch deviation and constant yaw deviation. These are provided for yaw deviations from -30 degrees to +30 degrees in increments of 5 degrees.

The solid blue lines are plots of the centerline displacement as a function of pitch deviations with zero yaw deviation and constant roll deviation. These are to be used, however, for any combination of yaw and roll deviations. They are provided for roll errors from -30 degrees to plus 30 degrees in 7.5 degree increments. The dotted blue lines represent 5 degree increments of pitch deviation.

The charts are used as follows. Starting at the center, follow the red line passing through the center the distance indicated by the yaw attitude deviation (outer gimbal angle reading). Each green line crossed represents 5 degrees of yaw. The positive and negative yaw values are indicated for each green line. Next move parallel to the nearest green line the distance indicated by the roll attitude deviation (middle gimbal angle reading). Each red line crossed represents a 5 degree increment of roll deviation. Finally, move parallel to the nearest solid blue line the distance indicated by the pitch deviation (inner gimbal angle reading). The dotted blue lines represent 5 degree increments of pitch deviation. The final stopping point represents the new center of the field of view for the particular detent.

The overlays on the charts are enlarged reproductions of one set of star charts from Reference 3. They represent the views of the star field for a landing at the prime Apollo 13 site (Fra Mauro) at the approximate time of the first IMU alignment. The star names are given in Table 3. The lines attached to each star show its path of motion during the surface stay time. The orientation of the star charts on the field of view locator charts is determined by matching the arrows radiating from the origin on each chart. These arrows indicate the zenith direction. Figure 8 presents a movable field of view indicator. When the center of Figure 8 is placed at the new center of the field of view, the new view of the stars will be indicated by the circle on Figure 8.

It should be noted that the attitude deviation charts are not dependent on time of landing or landing site. They may be used with any set of star charts of the form of Reference 3.

In order to determine reticle rotation as well as centerline displacement, proceed as follows. Place Figure 8 on the detent attitude deviation chart of interest such that the cross hairs are lined up with those on the star chart. These cross hairs represent the reticle as viewed through the AOT. Trace the path previously described with the center of Figure 8 but maintain a constant angle between the reticle lines and the chart line being followed. When this is completed, the reticle pattern on Figure 8 will be correctly oriented with respect to the star field.

For the front (#2) and rear (#5) detents, the centerline displacement plots for pitch form a family of curves as before. In addition, the centerline displacement plots for roll very nearly overlay the plots for yaw. In order to make the resulting chart readable, it was necessary to combine the motion due to roll and the motion due to yaw into a single trace. Since a large yaw deviation is more likely* than a large roll deviation, it was decided to bias the yaw-roll trace in favor of greater accuracy for yaw deviations. An approximation to the combined yaw-roll deviation was constructed as follows. The detent centerline location for a yaw deviation of 15° and a roll deviation of ± 5°** was chosen as a base point. A base line was constructed through the base point by calculating modified yaw and modified roll deviations and then finding the location of the detent center on the star chart for the LM in the attitude defined by these modified deviations. The modified deviations were calculated as follows. First, a number, n, was defined as:

$$n = \frac{\text{true yaw deviation} \pm \text{true roll deviation}}{5}\text{**}$$

and was then used to define the modified deviations:

$$\text{modified yaw} = 10° + 2.5\ n$$

$$\text{modified roll} = 10° - 2.5\ n$$

Only positive values of n were used. The points on the base line were then assigned a value, d, according to:

$$d = \text{modified yaw} \pm \text{modified roll}\text{**}$$

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*A cross range redesignation during landing can easily result in a substantial yaw error, whereas astronauts undoubtedly will tend to pick flat landing areas which results in smaller expected roll deviations.

**The minus is used for the front (#2) detent and the plus sign is used for the rear (#5) detent.

Thus, integer values of n produce 5° increments in d. As only positive values of n were used, only positive values of d were obtained. The base line location for negative values of d was defined to be the reflection of the positive base line about the vertical axis. The base line goes through the base point since the modified yaw and roll equal the true yaw and roll at this point. The base line so drawn is a single line approximation to the centerline traces for yaw and roll deviations when the base line values, d, are interpreted as:

$$d = \text{true yaw} \pm \text{true roll}^*$$

The centerline traces for pitch deviations were then approximated by calculating the centerline traces for pitch deviations from fixed values of d. Other approximation procedures were tried, but this one seemed to provide the best balance. Figures 5 and 6 show the resulting charts, again with the star fields for Apollo 13. The red trace labeled zero pitch is the base line. The other red lines represent the combined yaw-roll traces for constant values of pitch deviation. The blue lines are the pitch traces for constant values of combined yaw-roll deviation. These charts are used by adding or subtracting the yaw and roll deviations as appropriate for the detent. Starting at the crossing point of the zero yaw-roll and the zero pitch traces, follow the red yaw-roll trace to the resulting value. Each blue line crossed represents an increment of 5 degrees. Next move parallel to the blue pitch traces to the value of pitch deviation. Each red line represents an increment of 5 degrees. The reticle rotation cannot be found from these two charts.

The utility of these attitude error charts depends, of course, on their accuracy and readability. This was tested for the side detents by giving four subjects brief instructions and then asking them to try some sample problems. Table 1 tabulates the results of this test. The errors are expressed in terms of the distance on a great circle between the true centerline positions and the subject's solutions. The errors tabulated contain both the basic approximation errors inherent in the charts and the errors made by the subjects in reading the charts. The largest error was less than 1.5° and the average error was only .5°. Since the front and rear detent charts are quite simple, they were tested for the accuracy of the

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*The minus is used for the front (#2) detent and the plus sign is used for the rear (#5) detent.

approximations used only, not their readability. The accuracy was found by calculating the distance between the true center line position and the position found from the approximation formula for a series of cases. The result is tabulated in Table 2. The errors were found to be almost completely insensitive to deviations in pitch. The maximum error was 5.8°, though this occurred for an extreme case. The average error was 3°. It is felt that these results show that the field of view locator charts can be used with sufficient accuracy for the purposes of the star charts.

There is, in addition to the above errors, a distortion of the star pattern which is inherent in the projection chosen. The star charts and the field of view locator charts use an azimuthal equidistant projection.* As a result, the star patterns are distorted when the detent centerline is displaced. The nature of the distortion is shown in Figure 7. In the figure, the true location and shape of the detent reticle for a set of attitude deviations are plotted as solid lines. A representation of the detent as a circle is plotted with dashed lines, centered on the true reticle center. While the two detent edges match fairly well, the cross hairs are distorted. The distortion is not sufficient to impair the chart usefulness, however, even for this extreme case.

AOT Field of View Locator User's Guide

The AOT detent field of view locator charts of Figures 1 through 6 are used in a straightforward fashion. There is a slight variation in procedure between the side detents (numbers 1, 3, 4, and 6) and the front and rear detents (numbers 2 and 5). Consequently, separate procedures are provided here for each set.

Procedure for Side Detents (Detents 1, 3, 4, and 6)

1. Obtain the IMU gimbal angles from the DSKY display. This must be done after landing while the IMU is still aligned in the landing site alignment.

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*Using the center of the nominal field of view as the origin, this projection preserves the azimuth difference between any pair of stars, and the separation angle between a star and the centerline is mapped linearly along the radial direction.

2. Starting at the center, follow the red trace for the distance indicated by the yaw (outer gimbal angle) deviation. Each green line crossed represents 5° of yaw. Positive and negative directions are indicated by arrows.

3. From the point obtained in 2, move parallel to the nearest green trace through the distance indicated by the roll (middle gimbal angle) deviation. Each solid blue line crossed represents 5° of roll. Positive and negative directions are indicated by arrows.

4. From the point obtained in 3, move parallel to the nearest solid blue trace through the distance indicated by the pitch (inner gimbal angle) deviation. Each dotted blue line crossed represents 5° of pitch. Again, arrows indicate the direction for positive pitch deviations.

5. Place the center of the AOT field of view indicator (Figure 8) at the point obtained in Step 4. The stars seen in the AOT detent are those contained within the limits of the field of view indicator. An opaque sheet can now be inserted between the star chart and the locator chart to eliminate the "background noise" the locator chart creates.

6. If it is desired to obtain the orientation of the reticle cross hairs, Steps 2, 3, and 4 should be followed using the field of view indicator to trace the path to the solution. To begin with, the field of view indicator cross hairs are aligned with those of the star chart. Then, as the indicator is moved according to Steps 2, 3, and 4, the angle between the centerline trace followed and the cross hairs is held constant. At the end of Step 4, the stars contained in the field of view indicator will have the proper orientation relative to the cross hairs.

An example of the above procedure has been worked out for detent number 3 and is presented in Figure 9. The figure shows the path to be followed to obtain the solution for attitude deviations of:

yaw = +14° (outer gimbal angle)

roll = -9° (middle gimbal angle)

pitch = -13° (inner gimbal angle)

The solution can be easily followed by overlaying Figure 9 on Figure 2. The numbers on Figure 9 refer to the steps in the procedure given above.

Procedure for Front and Rear Detents

1. Obtain the IMU gimbal angles from the DSKY. This must be done after landing while the IMU is still in the landing site alignment.

2a. For the front detent, determine the value of yaw (outer gimbal angle) minus roll (middle gimbal angle). (Subtract algebraically). Use the result in Step 3.

2b. For the rear detent, determine the value of yaw (outer gimbal angle) plus roll (middle gimbal angle). (Add algebraically). Use the result in Step 3.

3. Starting at the point indicated for zero yaw-roll and zero pitch, follow the red yaw-roll trace the distance determined in Step 2. Each blue line crossed represents 5° of yaw-roll. The arrows indicate the positive direction.

4. From the point obtained in 3, move parallel to the nearest blue pitch trace the distance indicated by the pitch (inner gimbal angle) deviation. Each red line crossed represents 5°. Again arrows are provided indicating the positive direction.

5. Place the center of the field of view indicator at the point obtained in 4. The stars seen in the AOT detent are those contained within the limits of the field of view indicator. An opaque sheet can now be inserted between the star chart and the locator chart to eliminate the "background noise" caused by the locator chart.

6. The orientation of the field of view to the reticle cannot be found for these two detents.

K. M. Carlson

2011-KMC-vh

K. M. Carlson

Attachments
Tables 1 and 2
Figures 1-9

REFERENCES

1. Cauwels, G. M., Yang, T. L., "Stars and Planets Visible in the LM AOT During the Lunar Stay Time of the G Mission", Bellcomm Memorandum for File, B69 06099, June 27, 1969.

2. Yang, T. L., "Stars and Planets Visible in the LM AOT During the Lunar Stay Time of the Apollo 12 Mission", Bellcomm Memorandum for File, B69 09093, September 29, 1969.

3. Yang, T. L., "Stars and Planets Visible in the LM AOT During the Lunar Stay Time of the Apollo 13 Mission", Bellcomm Memorandum for File, to be published.

Table 1

The Error in Reading the Detent Centerline Motion Displays Compared to True Values for Detents Number One, Three, Four, and Six

Yaw Deviation	Roll Deviation	Pitch Deviation	Centerline Error (Great Circle Deg.) Subject No.* 1	2	3	4	Average
+20	+15	+15	.93	.14	.77	.75	.65
+20	+15						
+20	+15	-15	.22	.22	.44	.87	.44
+20	-15	+15	.14	.14	.37	.46	.28
+20	-15						
+20	-15	-15	.40	.40	.20	.91	.48
-20	+15	+15	.73	.45	.54	1.37	.77
-20	+15	-15	.77	.13	.31	.42	.41
-20	-15	+15	.08	.17	.67	.56	.37
-20	-15	-15	.59	.59	.69	.13	.50
Average			.48	.28	.50	.68	.48

*Subjects were all members of the Trajectory Mechanics Group, Bellcomm, Inc.

Table 2

The Deviation of the Detent Centerline Position from the True Value for Detent Numbers Two and Five (Front and Rear).

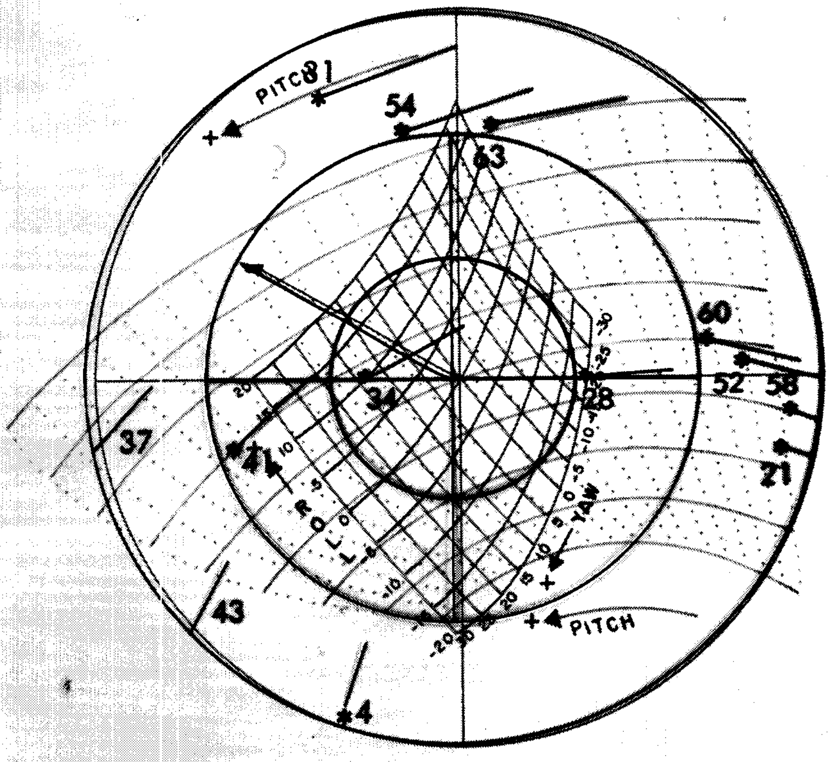
Yaw Deviation	Roll Deviation	Centerline Deviation* (Great Circle Deg.)
0	-20	3.46
0	0	.87
0	20	3.46
15	-20	4.55
15	0	.70
15	20	.81
30	-20	2.74
30	0	2.34
30	20	5.77

*The centerline deviation shows little variation as a function of pitch deviation.

STAR NO.	NAME
1	ALPHERATZ (α ANDROMEDAE)
2	DIPHDA (β CETI)
3	NAVI (γ CASSIOPEIAE)
4	ACHERNAR (α ERIDANI)
5	POLARIS (α URSAE MINORIS)
6	ACAMAR (θ ERIDANI)
7	MENKAR (α CETI)
8	MIRFAK (α PERSEI)
9	ALDEBARAN (α TAURI)
10	RIGEL (β ORIONIS)
11	CAPELLA (α AURIGAE)
12	CANOPUS (α CARINAE)
13	SIRIUS (α CANIS MAJORIS)
14	PROCYON (α_2 CANIS MINORIS)
15	REGOR (γ VELORUM)
16	DNOCES (ι URSAE MAJORIS)
17	ALPHARD (α HYDRAE)
18	REGULUS (α LEONIS)
19	DENEBOLA (β LEONIS)
20	GIENAH (γ CORVI)
21	ACRUX (α CRUCIS)
22	SPICA (α VIRGINIS)
23	ALKAID (η URSAE MAJORIS)
24	MENKENT (θ CENTAURI)
25	ARCTURUS (α BOOTIS)
26	ALPHECCA (α CORONAE BOREALIS)
27	ANTARES (α SCORPII)
28	ATRIA (α TRIANGULI)
29	RASALHAGUE (α OPHIUCHI)
30	VEGA (α LYRAE)
31	NUNKI (σ SAGITTARII)
32	ALTAIR (α AQUILAE)
33	DABIH (β CAPRICORNI)
34	PEACOCK (α PAVONIS)
35	DENEB (α CYGNI)
36	ENIF (ϵ PEGASI)
37	FOMALHAUT (α PISCIS AUSTR.)
38	ADHARA (ϵ CANIS MAJORIS)
39	ALHENA (γ GEMINORUM)
40	ALIOTH (ϵ URSAE MAJORIS)
41	AL NA ' IR (α GRUIS)
42	ALNILAM (ϵ ORIONIS)
43	ANKAA (α PHOENICIS)
44	AVIOR (ϵ CARINAE)
45	BELLATRIX (γ ORIONIS)
46	BETELGEUSE (α ORIONIS)
47	CASTOR (α GEMINORUM)
48	DUBHE (α URSAE MAJORIS)
49	ELNATH (β TAURI)
50	ELTANIN (γ DRACONIS)
51	GACRUX (γ CRUCIS)
52	HADAR (β CENTAURI)
53	HAMAL (α ARIETIS)
54	KAUS AUSTRALIS (ϵ SAGITTARII)
55	KOCHAB (β URSAE MINORIS)
56	MARKAB (α PEGASI)
57	MIAPLACIDUS (β CARINAE)
58	MIMOSA (β CRUCIS)
59	POLLUX (β GEMINORUM)
60	RIGEL KENTAURUS (α CENTAURI)
61	SABIK (η OPHIUCHI)
62	SCHEDAR (α CASSIOPEIAE)
63	SHAULA (λ SCORPII)
64	SUHAIL (λ VELORUM)
65	ALNITAK (ζ ORIONIS)

TABLE 3 STARS CONSIDERED

DETENT NO. 1
(LEFT FORWARD)



DETENT NO. 3
(RIGHT FORWARD)

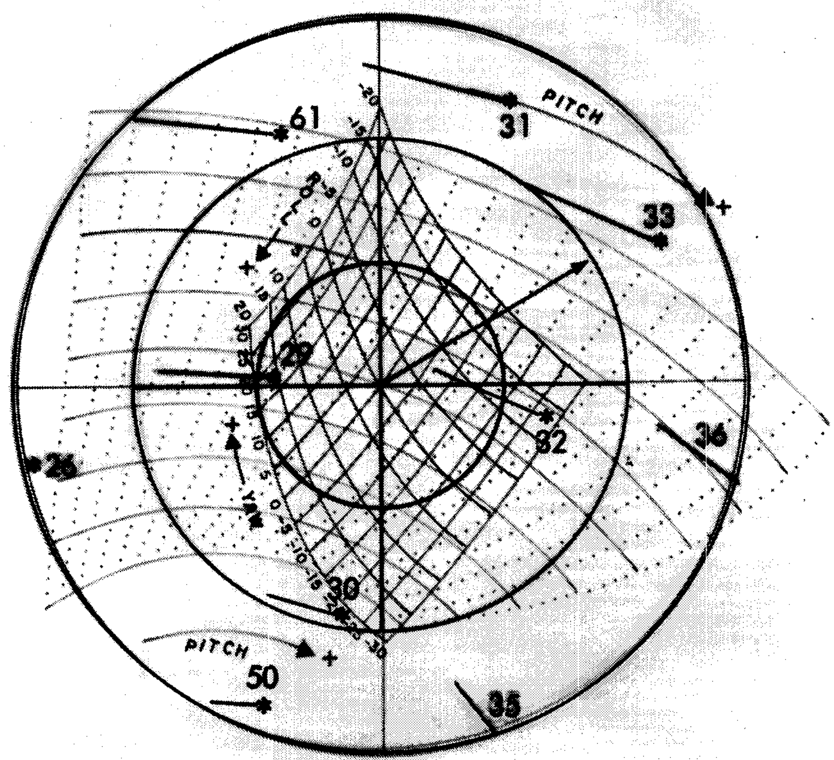


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FIGURE 1 AOT DETENT FIELD OF VIEW LOCATOR FOR THE AOT STAR CHARTS WITH LM ATTITUDE DEVIATIONS–DETENT NO. 1

FIGURE 2 AOT DETENT FIELD OF VIEW LOCATOR FOR THE AOT STAR CHARTS WITH LM ATTITUDE DEVIATIONS–DETENT NO. 3

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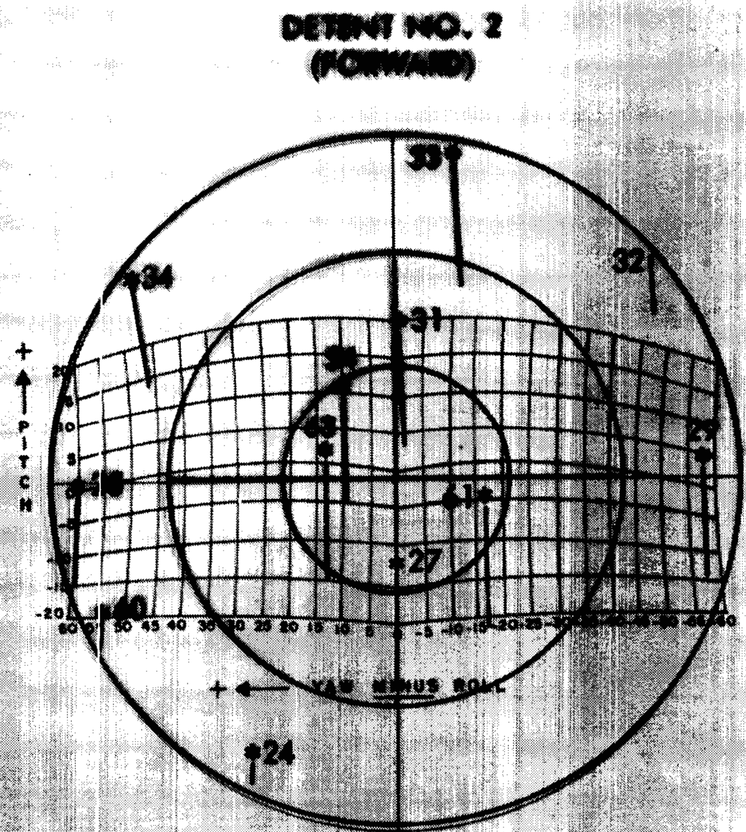

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FIGURE 5- AOT DETENT FIELD OF VIEW LOCATOR FOR THE AOT STAR CHARTS WITH LM ATTITUDE DEVIATIONS—DETENT NO. 2

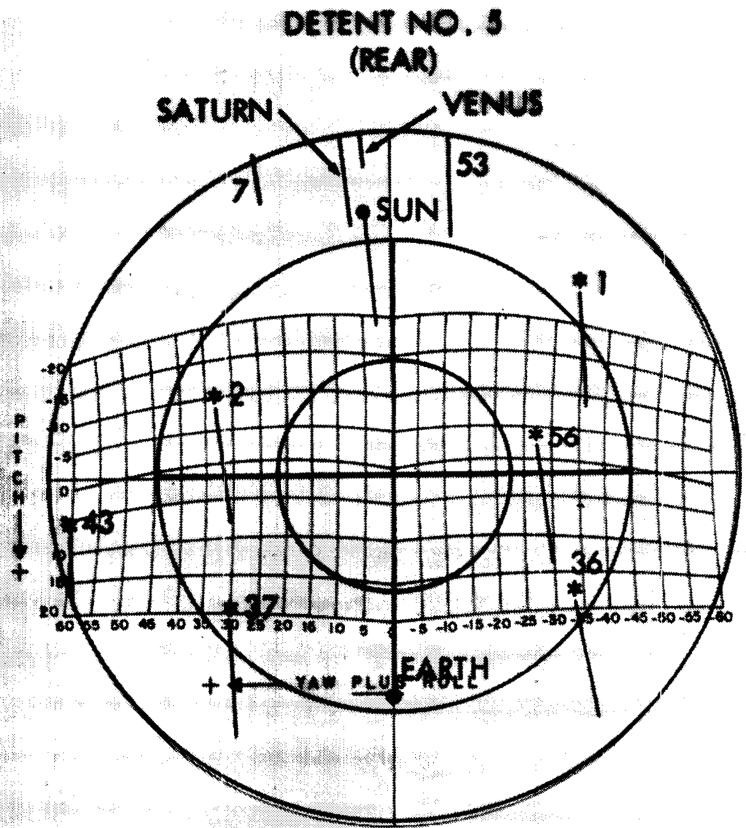

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FIGURE 6- AOT DETENT FIELD OF VIEW LOCATOR FOR THE AOT STAR CHARTS WITH LM ATTITUDE DEVIATIONS—DETENT NO. 5

DETENT NO. 4
(RIGHT REAR)

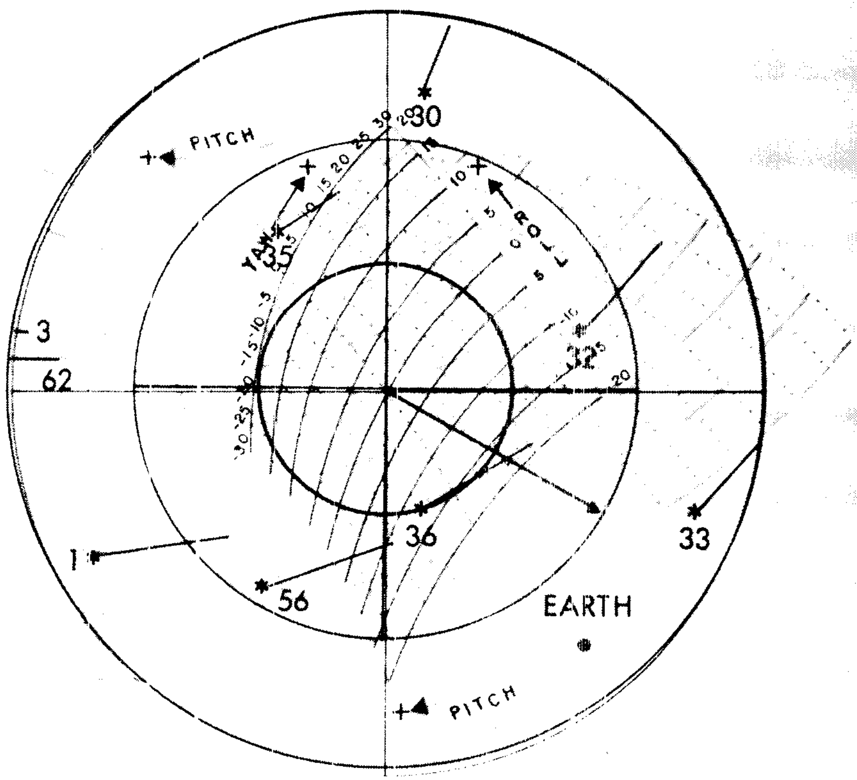

FIGURE 3 AOT DETENT FIELD OF VIEW LOCATOR FOR THE AOT STAR CHARTS WITH LM ATTITUDE DEVIATIONS DETENT NO. 4

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DETENT NO. 6
(LEFT REAR)

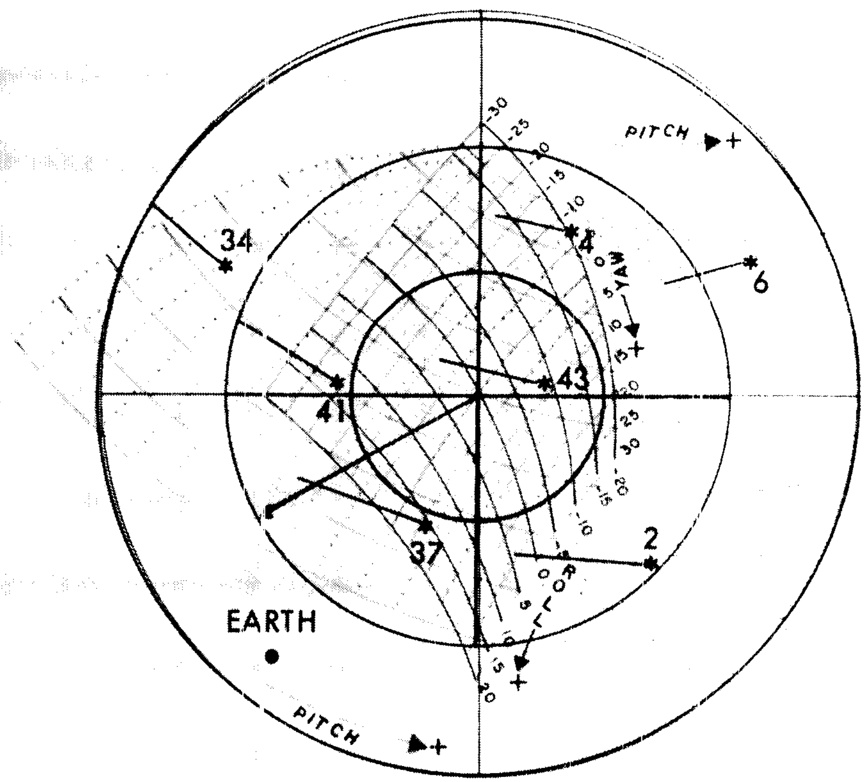

FIGURE 4 AOT DETENT FIELD OF VIEW LOCATOR FOR THE AOT STAR CHARTS WITH LM ATTITUDE DEVIATIONS DETENT NO. 6

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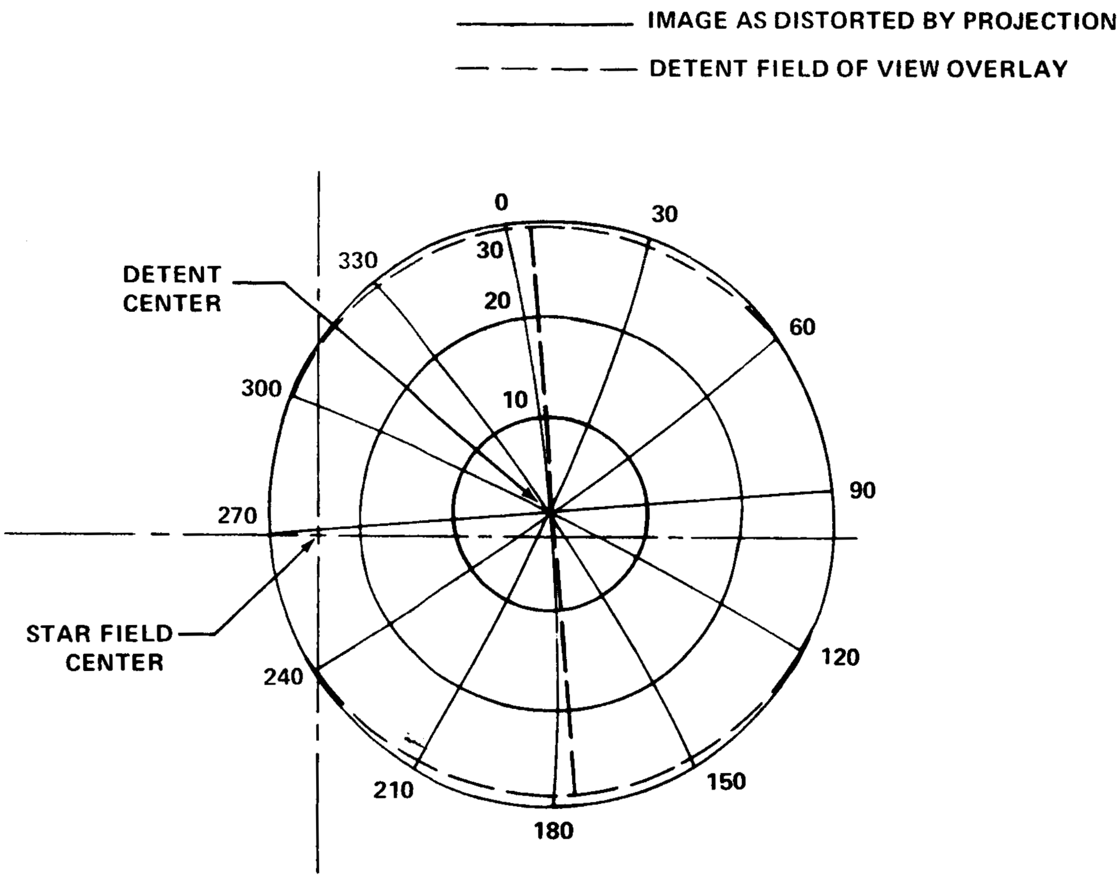


FIGURE 7 - PATTERN DISTORTION ON AN AZIMUTHAL-EQUIDISTANT PROJECTION FOR A -20° YAW, 10° ROLL, -20° PITCH IN DETENT NO. 1

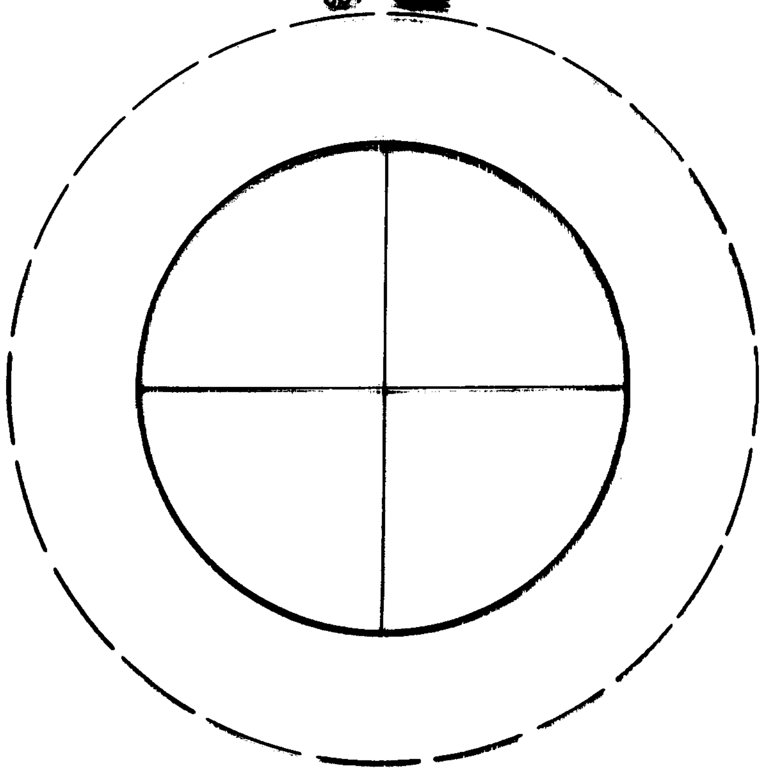
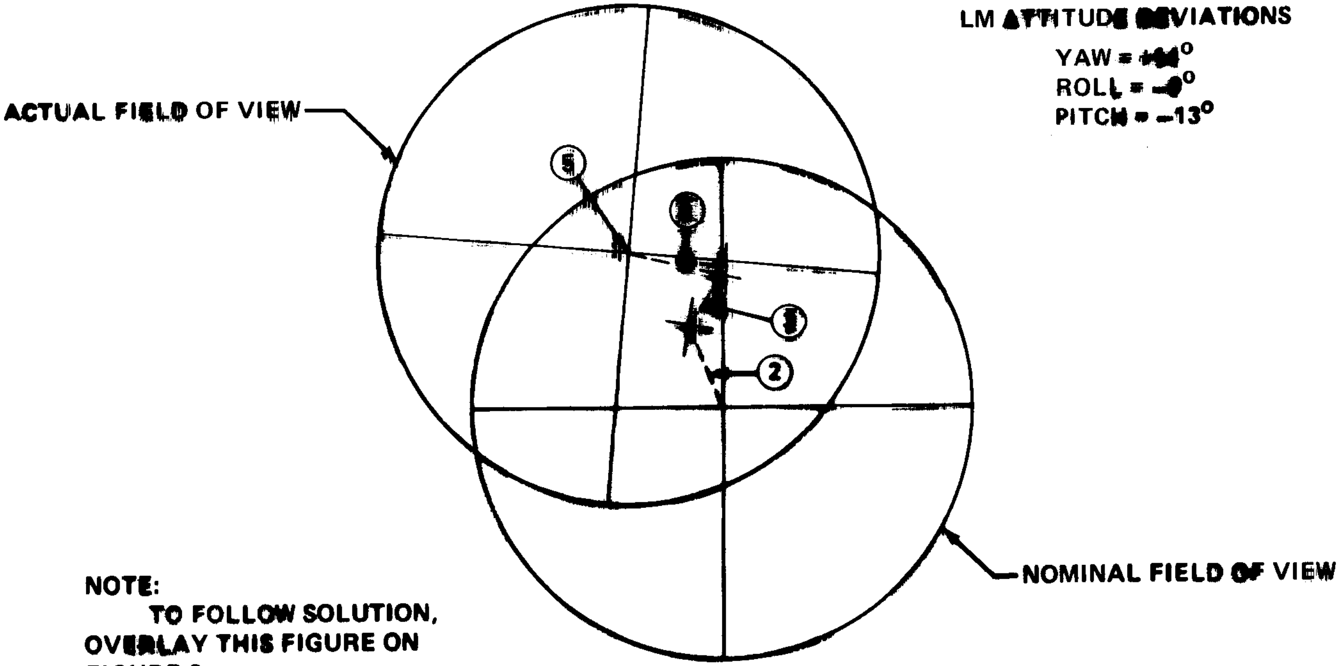


FIGURE 8 - AGT DETENT FIELD OF VIEW INDICATOR



NOTE:
TO FOLLOW SOLUTION, OVERLAY THIS FIGURE ON FIGURE 2.

FIGURE 9 – LOCATION OF THE FIELD OF VIEW OF DETENT NO. 3 FOR AN EXAMPLE SET OF ATTITUDE DEVIATIONS